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Gue et al.

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(54) **AUTOMATED ITEM SEQUENCING IN A HIGH-DENSITY GRID-BASED MATERIAL HANDLING SYSTEM**

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(51) **Int. Cl.**

G06F 7/00	(2006.01)
B65G 1/137	(2006.01)
G06Q 10/08	(2012.01)

(52) **U.S. Cl.**

CPC ***B65G 1/1378*** (2013.01); *G06Q 10/087* (2013.01)

(58) **Field of Classification Search**

USPC 700/214

See application file for complete search history.

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U.S. Appl. No. 61/888,332, filed Oct. 8, 2013.

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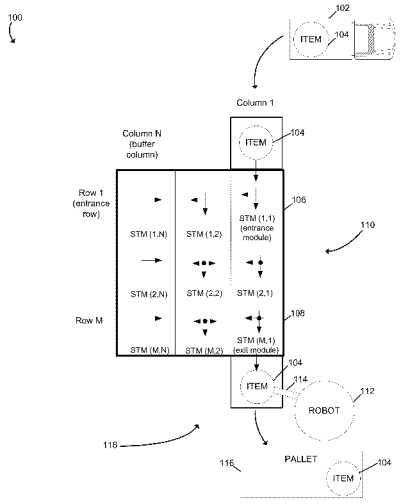
(57) **ABSTRACT**

Randomly presented physical items can be temporarily stored in a grid-based material handling system, e.g., before they are handled by a robot. The grid-based material handling system arranges the randomly presented physical items within the grid, so that they exit the grid in an ordered sequence, e.g., for pickup by the robot. Programmable modules execute sequencing logic to move the items to target locations within the grid. The modules move interfering items out of the way of other items that are in transit to their target locations, as needed. The programmable modules allow the items to exit the grid when the requirements of a departure policy are met.

20 Claims, 8 Drawing Sheets



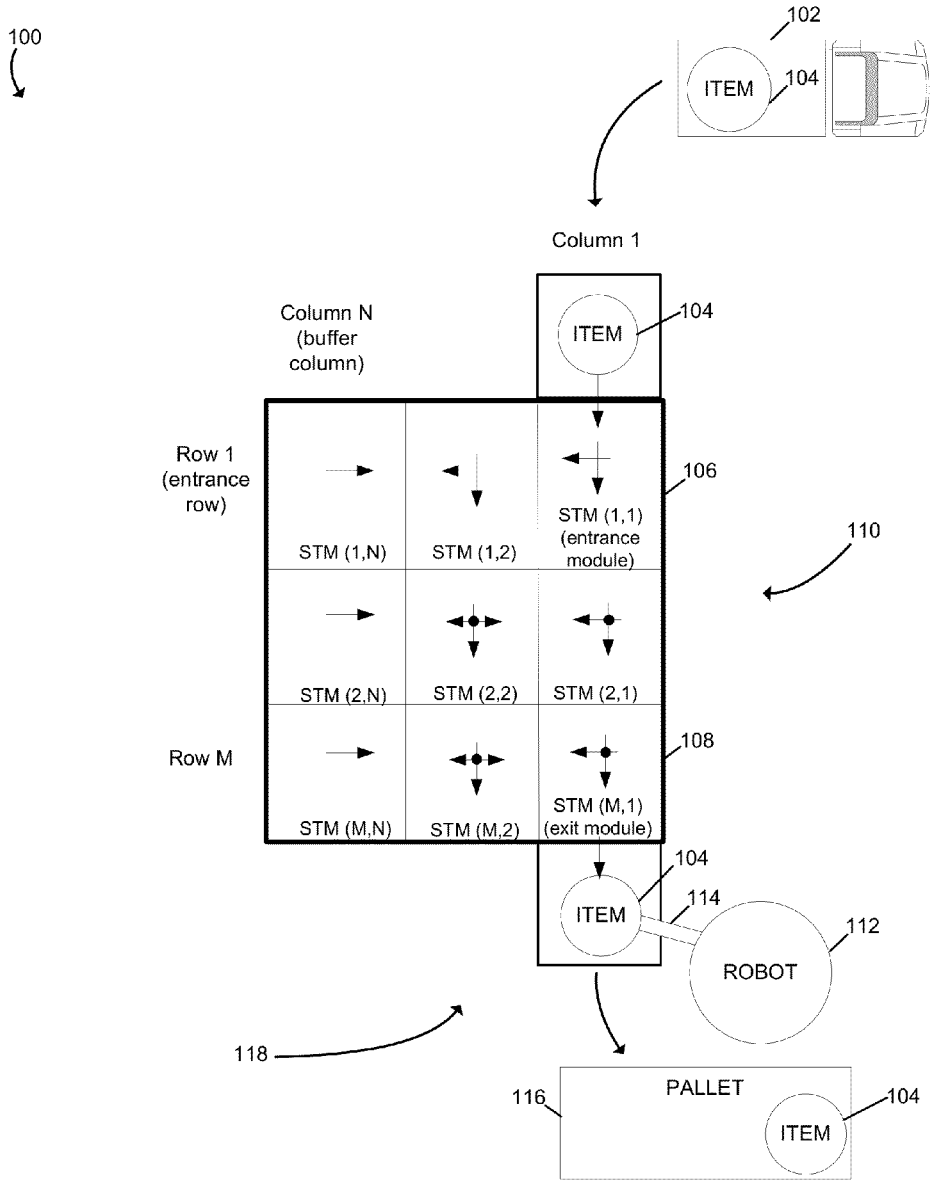

100
102
ITEM
104
Column 1
Column N
(buffer
column)
ITEM
104
Row 1
(entrance
row)
106
STM (1,1)
(entrance
module)
110
STM (1,N)
STM (1,2)
STM (2,N)
STM (2,2)
STM (2,1)
Row M
108
STM (M,N)
STM (M,2)
STM (M,1)
(exit module)
104
ITEM
114
112
ROBOT
118
116
PALLET
104
ITEM

FIG. 1

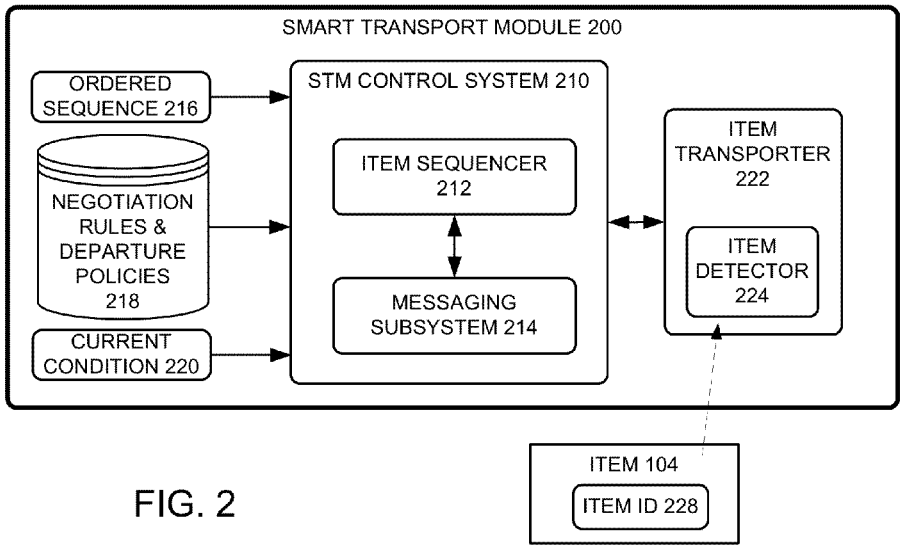

SMART TRANSPORT MODULE 200
ORDERED SEQUENCE 216
NEGOTIATION RULES & DEPARTURE POLICIES 218
CURRENT CONDITION 220
STM CONTROL SYSTEM 210
ITEM SEQUENCER 212
MESSAGING SUBSYSTEM 214
ITEM TRANSPORTER 222
ITEM DETECTOR 224
ITEM 104
ITEM ID 228

FIG. 2

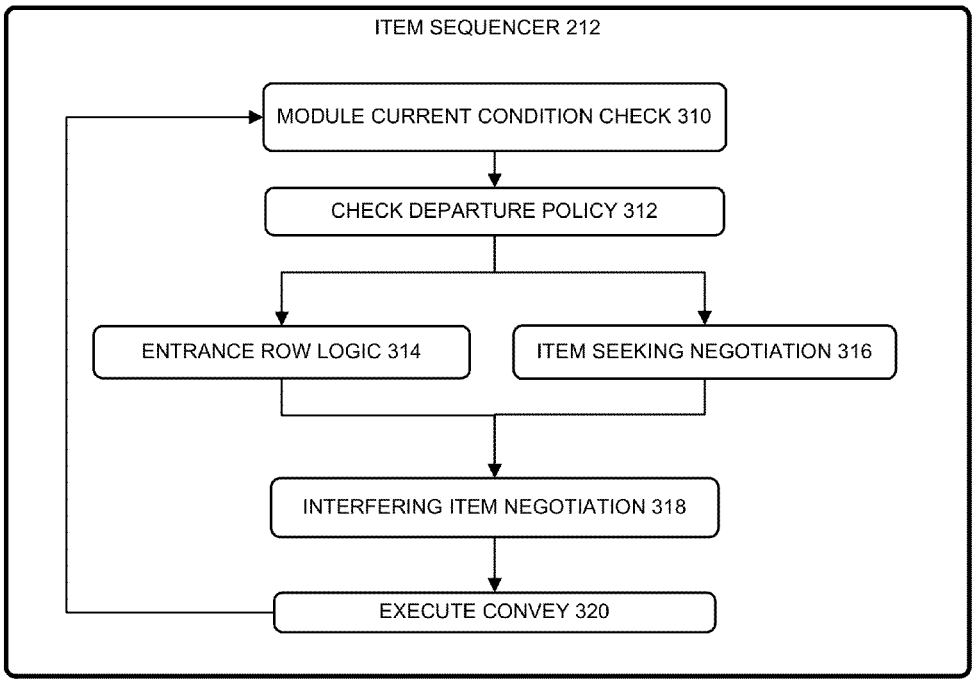

ITEM SEQUENCER 212
MODULE CURRENT CONDITION CHECK 310
CHECK DEPARTURE POLICY 312
ENTRANCE ROW LOGIC 314
ITEM SEEKING NEGOTIATION 316
INTERFERING ITEM NEGOTIATION 318
EXECUTE CONVEY 320

FIG. 3

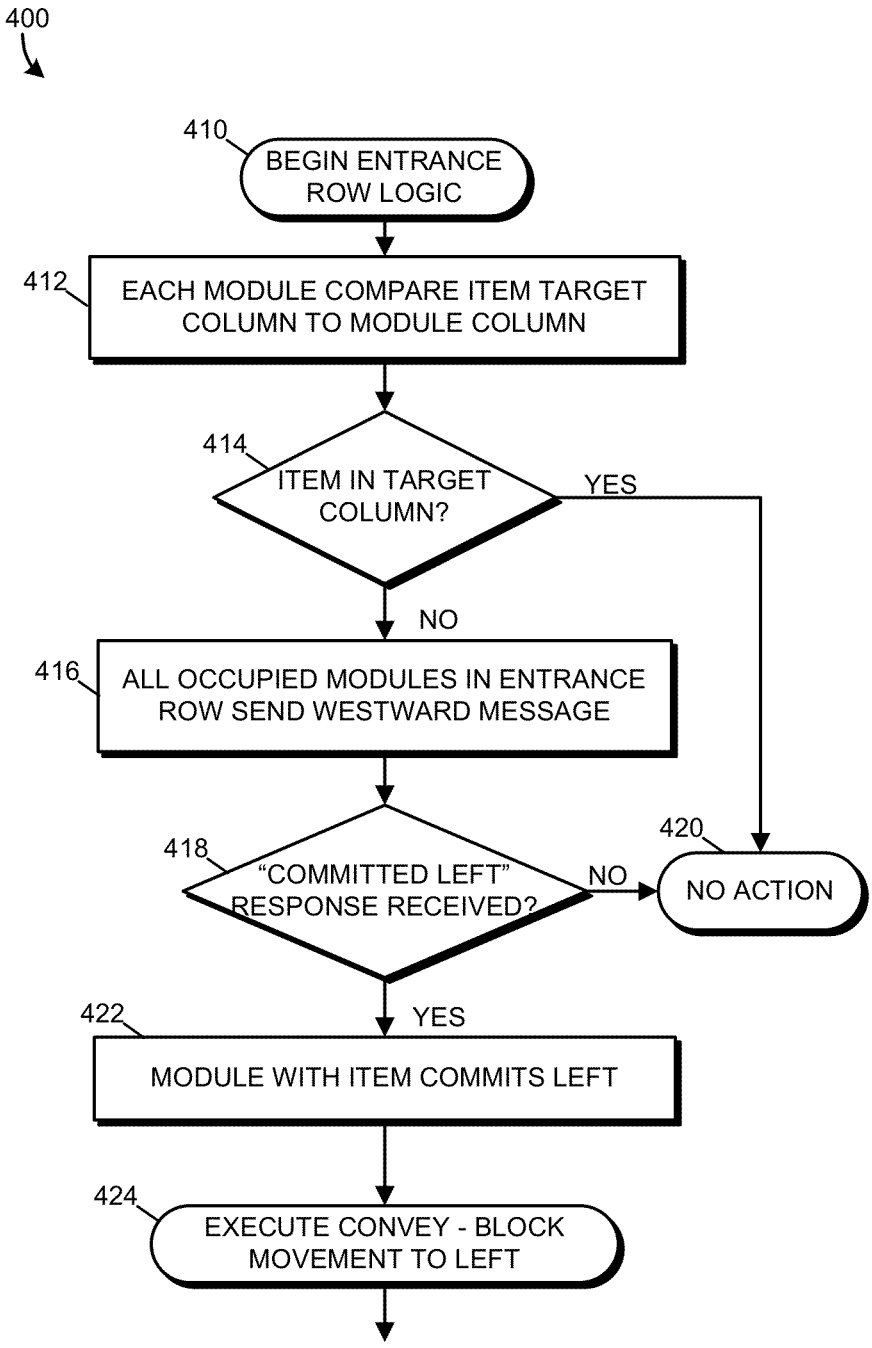

400
410
BEGIN ENTRANCE ROW LOGIC
412
EACH MODULE COMPARE ITEM TARGET COLUMN TO MODULE COLUMN
414
ITEM IN TARGET COLUMN?
YES
NO
416
ALL OCCUPIED MODULES IN ENTRANCE ROW SEND WESTWARD MESSAGE
418
"COMMITTED LEFT" RESPONSE RECEIVED?
NO
420
NO ACTION
YES
422
MODULE WITH ITEM COMMITS LEFT
424
EXECUTE CONVEY - BLOCK MOVEMENT TO LEFT

FIG. 4

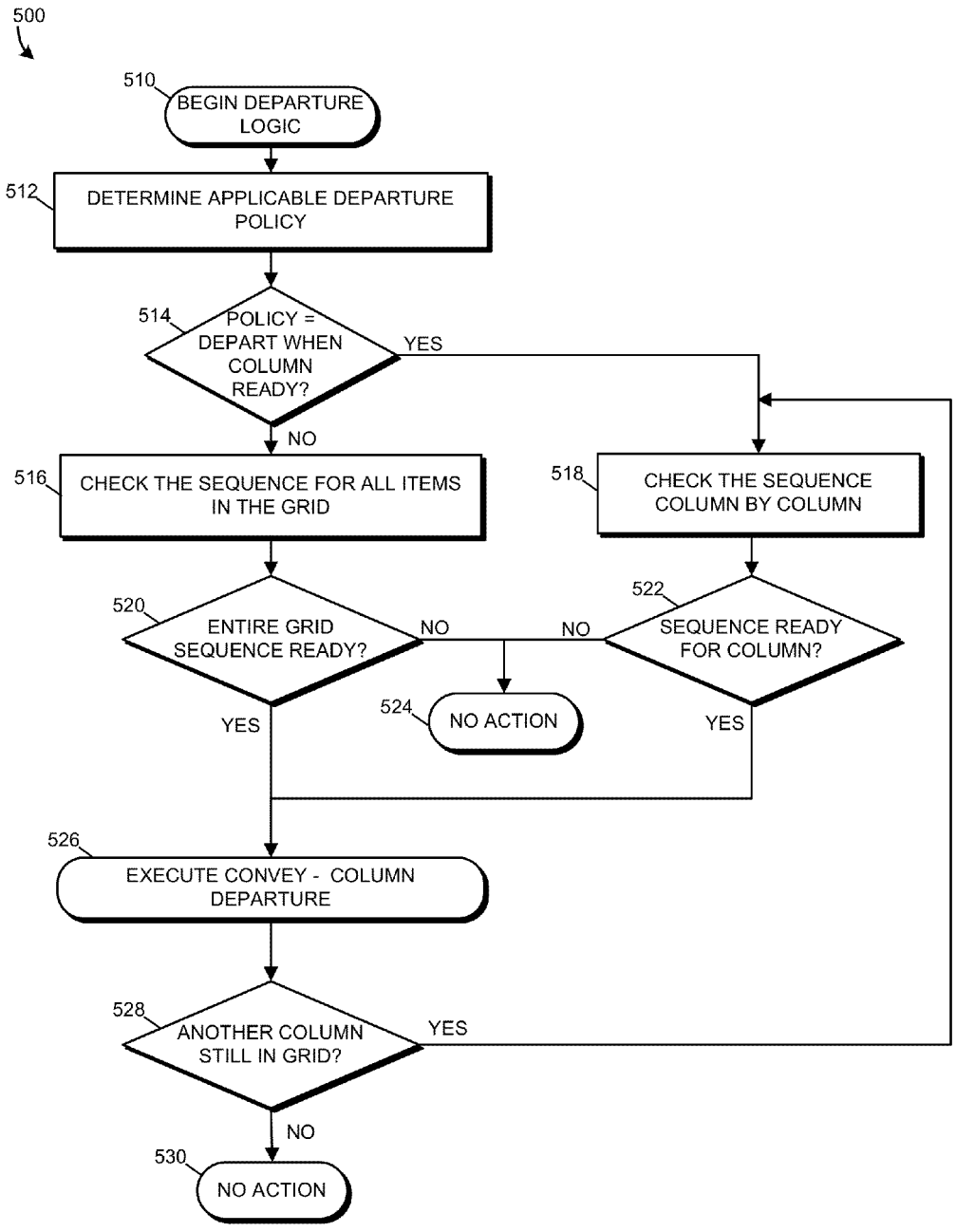

500
510
BEGIN DEPARTURE LOGIC
512
DETERMINE APPLICABLE DEPARTURE POLICY
514
POLICY = DEPART WHEN COLUMN READY?
YES
NO
516
CHECK THE SEQUENCE FOR ALL ITEMS IN THE GRID
518
CHECK THE SEQUENCE COLUMN BY COLUMN
520
ENTIRE GRID SEQUENCE READY?
NO
NO
522
SEQUENCE READY FOR COLUMN?
524
NO ACTION
YES
YES
526
EXECUTE CONVEY - COLUMN DEPARTURE
528
ANOTHER COLUMN STILL IN GRID?
YES
NO
530
NO ACTION

FIG. 5

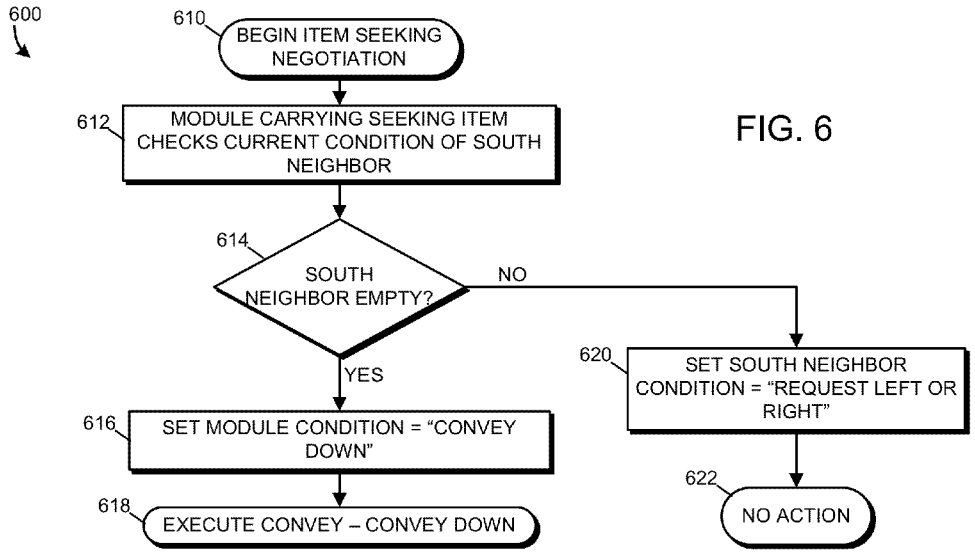

600
610
BEGIN ITEM SEEKING NEGOTIATION
612
MODULE CARRYING SEEKING ITEM CHECKS CURRENT CONDITION OF SOUTH NEIGHBOR
614
SOUTH NEIGHBOR EMPTY?
NO
YES
620
SET SOUTH NEIGHBOR CONDITION = "REQUEST LEFT OR RIGHT"
622
NO ACTION
616
SET MODULE CONDITION = "CONVEY DOWN"
618
EXECUTE CONVEY – CONVEY DOWN

FIG. 6

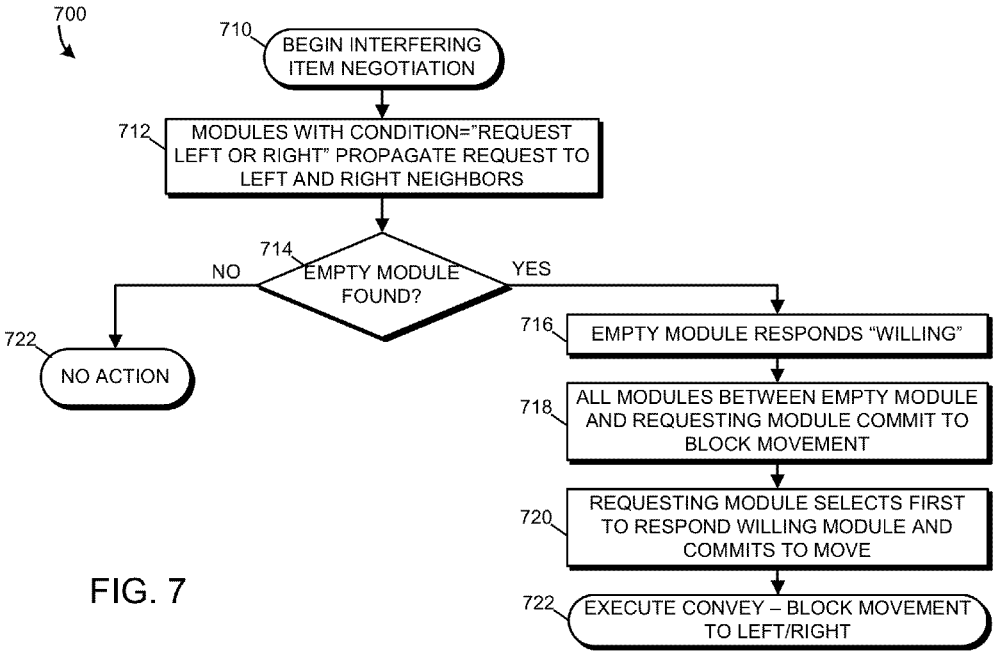

700
710
BEGIN INTERFERING ITEM NEGOTIATION
712
MODULES WITH CONDITION="REQUEST LEFT OR RIGHT" PROPAGATE REQUEST TO LEFT AND RIGHT NEIGHBORS
714
EMPTY MODULE FOUND?
NO
YES
722
NO ACTION
716
EMPTY MODULE RESPONDS "WILLING"
718
ALL MODULES BETWEEN EMPTY MODULE AND REQUESTING MODULE COMMIT TO BLOCK MOVEMENT
720
REQUESTING MODULE SELECTS FIRST TO RESPOND WILLING MODULE AND COMMITS TO MOVE
722
EXECUTE CONVEY – BLOCK MOVEMENT TO LEFT/RIGHT

FIG. 7

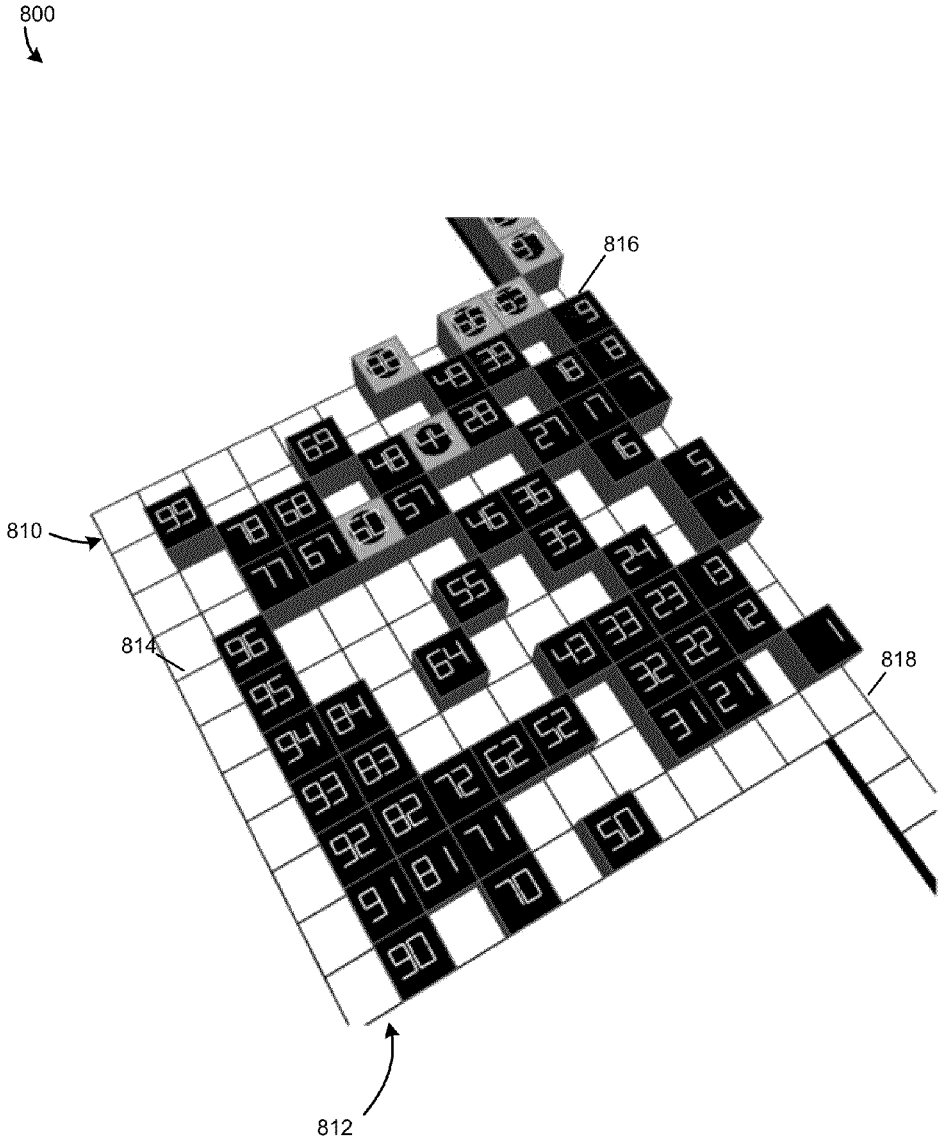


FIG. 8

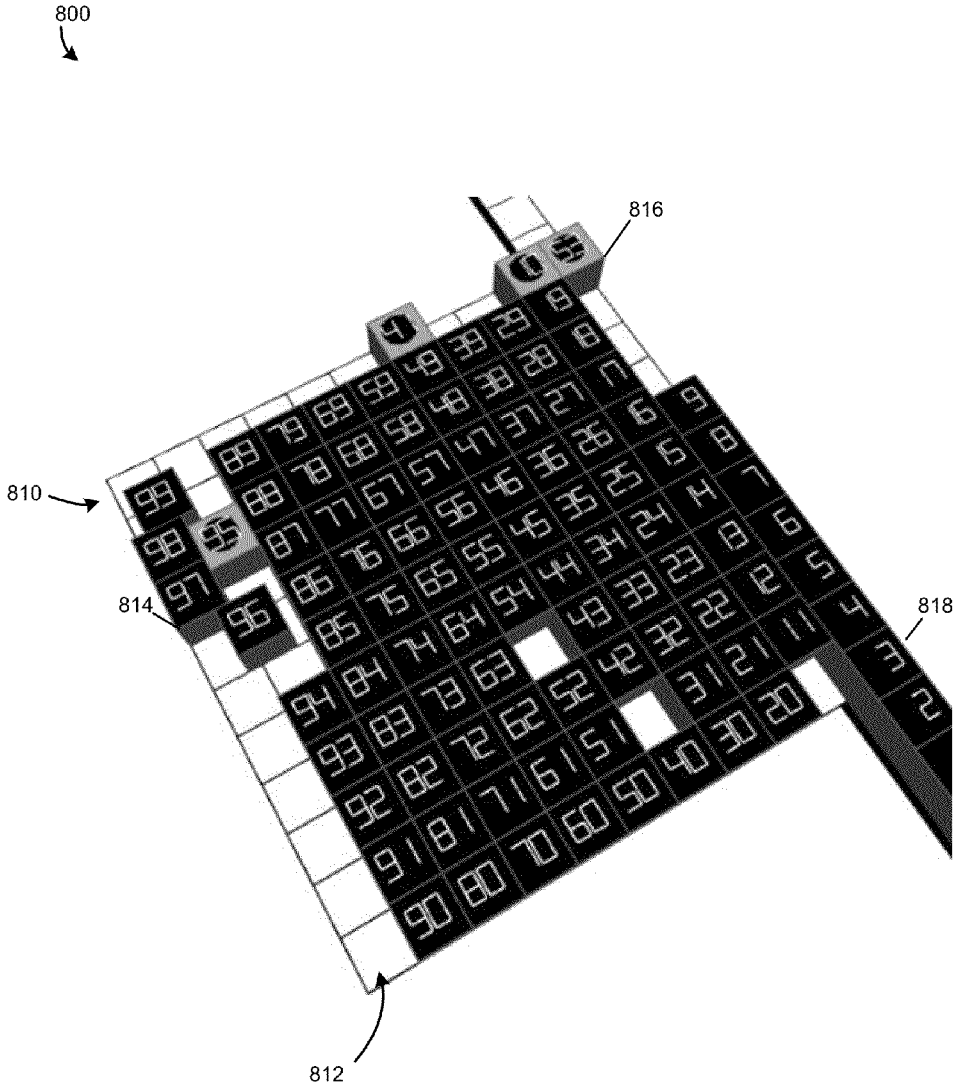


FIG. 9

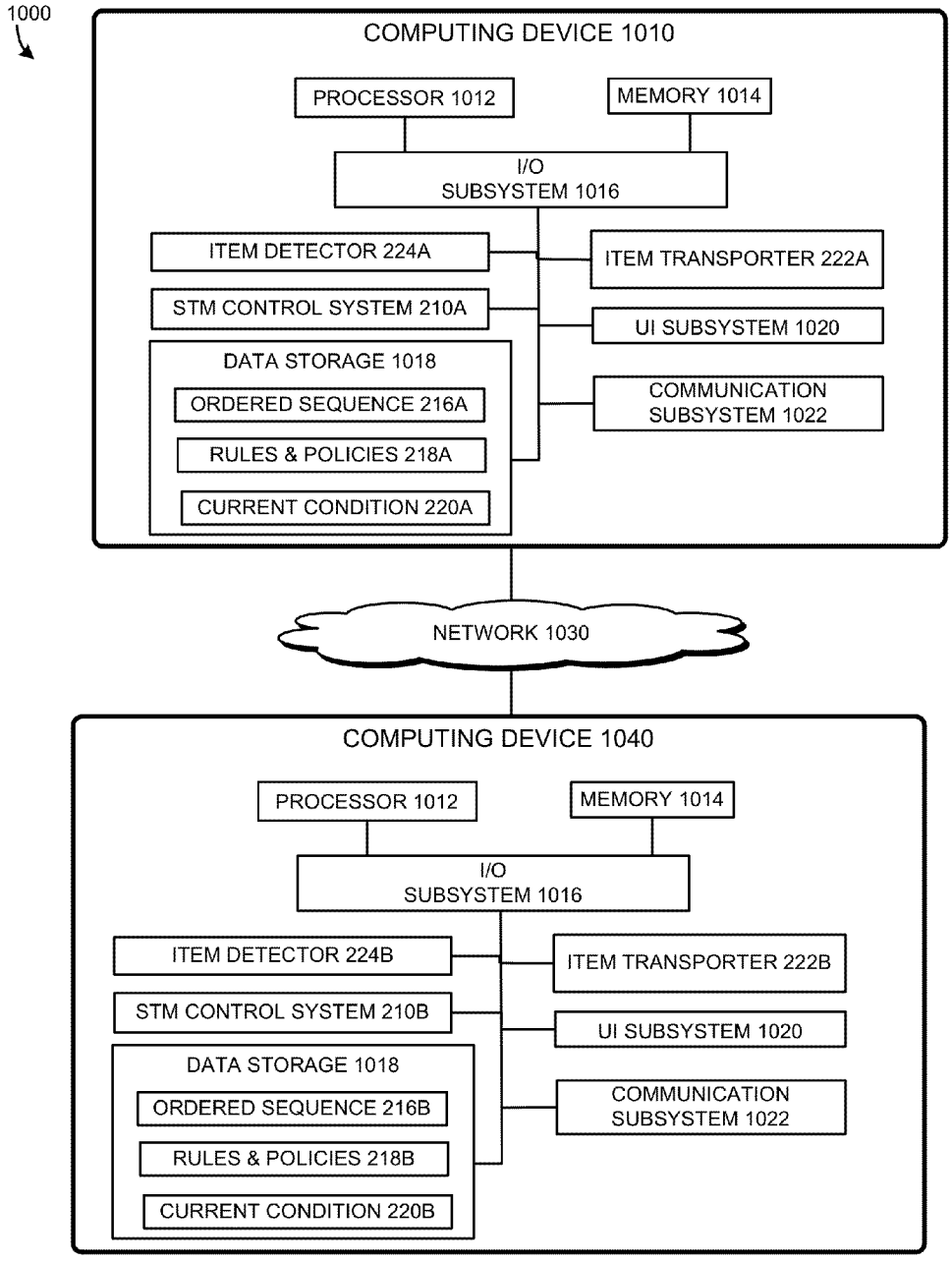

1000
COMPUTING DEVICE 1010
PROCESSOR 1012
MEMORY 1014
I/O SUBSYSTEM 1016
ITEM DETECTOR 224A
ITEM TRANSPORTER 222A
STM CONTROL SYSTEM 210A
UI SUBSYSTEM 1020
DATA STORAGE 1018
ORDERED SEQUENCE 216A
RULES & POLICIES 218A
CURRENT CONDITION 220A
COMMUNICATION SUBSYSTEM 1022
NETWORK 1030
COMPUTING DEVICE 1040
PROCESSOR 1012
MEMORY 1014
I/O SUBSYSTEM 1016
ITEM DETECTOR 224B
ITEM TRANSPORTER 222B
STM CONTROL SYSTEM 210B
UI SUBSYSTEM 1020
DATA STORAGE 1018
ORDERED SEQUENCE 216B
RULES & POLICIES 218B
CURRENT CONDITION 220B
COMMUNICATION SUBSYSTEM 1022

FIG. 10

AUTOMATED ITEM SEQUENCING IN A HIGH-DENSITY GRID-BASED MATERIAL HANDLING SYSTEM

CROSS-REFERENCES TO RELATED APPLICATIONS

This application claims priority to and the benefit of U.S. Provisional Patent Application Ser. No. 61/726,306, filed Nov. 14, 2012, and claims priority to and the benefit of U.S. Provisional Patent Application Ser. No. 61/734,603, filed Dec. 7, 2012, and claims priority to and the benefit of U.S. Provisional Patent Application Ser. No. 61/888,332, filed Oct. 8, 2013, each of which is incorporated herein by this reference in its entirety.

GOVERNMENT RIGHTS

This invention was made with government support under Contract CMM10926346 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND

In an automated material handling system, items, such as boxes or cartons, are loaded onto pallets by a robot. For example, in automotive assembly plants, mixed-model assembly lines sequence subassemblies or parts for final assembly. Preferably, the parts are delivered in sequence starting from the suppliers for the assembly lines. The sequence can be disrupted as a result of missing parts, delays, rework, parallel workstations, and other factors. Such disruptions require time consuming re-sequencing of the parts.

One approach to item sequencing involves an automated storage and retrieval system (AS/RS), which uses computer-controlled systems to place items into and retrieve items from defined storage locations. Items are retrieved from the AS/RS (typically by cranes) and fed to the robotic pallet building workstations. To do this, a warehouse management system constructs a desired sequence and releases requests to the AS/RS in accordance with the sequence. However, if there are multiple cranes working in parallel, for example, the requests are not always fulfilled in the proper order. As a result, items often arrive out of sequence.

Another way to achieve the sequence of items required by the palletizing robot is to use a circular sortation conveyor. Items enter and loop around the conveyor until they are required at the workstation. Some disadvantages of this system include increased cycle time of requested items, inflexibility with respect to throughput capacity, and poor utilization of floor space.

BRIEF DESCRIPTION OF THE DRAWINGS

This disclosure is illustrated by way of example and not by way of limitation in the accompanying figures. The figures may, alone or in combination, illustrate one or more embodiments of the disclosure. Elements illustrated in the figures are not necessarily drawn to scale. Reference labels may be repeated among the figures to indicate corresponding or analogous elements.

FIG. **1** is a simplified plan view diagram of at least one embodiment of an automated material handling system including a grid of programmable modules to sequence items as disclosed herein;

FIG. **2** is a simplified module diagram of at least one embodiment of a programmable module of FIG. **1**;

FIG. **3** is a simplified module diagram of at least one embodiment of the item sequencer of FIG. **2**;

FIG. **4** is a simplified flow diagram of at least one embodiment of a method by which the system of FIG. **1** may handle items entering the grid;

FIG. **5** is a simplified flow diagram of at least one embodiment of a method by which the system of FIG. **1** may handle the departure of items from the grid;

FIG. **6** is a simplified flow diagram of at least one embodiment of a method by which the system of FIG. **1** may transport items from one module to another in the grid;

FIG. **7** is a simplified flow diagram of at least one embodiment of a method by which the system of FIG. **1** may handle interfering items in the grid;

FIG. **8** is a simplified graphical depiction of the grid in a state in which items are in transport within the grid;

FIG. **9** is a simplified graphical depiction of the grid in a state in which items are departing the grid; and

FIG. **10** is a simplified block diagram of an exemplary hardware environment with which at least one embodiment of the computing system of FIG. **1** may be implemented.

DETAILED DESCRIPTION OF THE DRAWINGS

While the concepts of the present disclosure are susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and are described in detail below. It should be understood that there is no intent to limit the concepts of the present disclosure to the particular forms disclosed. On the contrary, the intent is to cover all modifications, equivalents, and alternatives consistent with the present disclosure and the appended claims.

Robotic pallet-building can reduce transportation and labor costs in the distribution industry and/or other industries. In a common application, robots pick cartons from a staging area and place them methodically on a pallet. Typical pallet-building objectives include: (1) to achieve a high packing density, (2) to adhere to product constraints (e.g., lighter items should be placed on top of heavier items), (3) to minimize inventory costs by shipping less-than-pallet quantities, and (4) to reduce labor costs in stores by placing items that are stocked close to one another in the store near to one another on the pallet. To achieve these and/or other objectives, a grid-based material handling system **100** as disclosed herein can arrange randomly-arriving items into a precise sequence for robotic placement on the pallet without the disadvantages of existing approaches. The grid-based material handling system **100** temporarily stores the items in their respective positions according to the sequence, and then releases the items in sequence when the items and all of the preceding items are in their proper positions.

Referring now to FIG. **1**, an embodiment of the grid-based material handling system **100** is shown. A carrier **102**, such as a truck or other transport vehicle, or other transport mechanism, typically delivers pallets of items **104** to a warehouse or other type of storage location. The items **104** arrive randomly at an entrance module **106** of the grid-based material handling system **100**. The entrance module **106** is part of a grid **110**, which is made up of a number of programmable modules STM(M,N), which are used to temporarily store the items **104** and to arrange the items **104** in an ordered sequence before they are delivered to a palletizer workstation **118**. The modules of the grid **110** operate to accomplish the ordered sequence. The ordered sequence is typically pre-defined (e.g.,

by a human operator of the system **100**, alone or with the assistance of computerized algorithms). At the palletizer workstation **118**, an end effector **114** of a robot **112** picks the items **104** from an exit module **108** of the grid **110** and places the items **104** on a pallet **116** in the order in which they arrive at the exit module **108**, which corresponds to the specified ordered sequence. The ordered sequence is typically a precise sequence in which the items **104** are to be picked by the robot **112**. The sequence is defined (usually in advance) by a person and/or a computing system in accordance with the requirements of a particular palletizing task. For example, the palletizing sequence may be defined to address one or more of the palletizing objectives listed above. While a single robot **112** is shown in FIG. **1** for simplicity, multiple robots may be employed in other embodiments. For example, the system **100** may be comprised of multiple grids **110**, each with its own robot, or a single robot may handle the picking of items from multiple grids (e.g., adjacent grids within the workspace of the end effector **114**). Further, multiple robots may work in combination with a single grid **110**, in some embodiments. For instance, one robot may pick a newly departed item while another robot is moving an already-picked item to the pallet **116**.

The illustrative grid **110** is a planar grid of initially unoccupied programmable modules. The grid **110** includes a number of rows, M, and a number of columns, N, of programmable modules STM(M,N), which may also be referred to herein as "smart transport modules" (where M and N are positive integers). Each module STM(M,N) is capable of conveying items in one or more of the four cardinal directions (north, south, east, west). In the illustrative embodiments described herein, each of the modules STM(M,N) can convey items in all of the four cardinal directions. The mechanical capabilities needed for this type of movement are commercially available in the material handling industry. An example of a programmable module that is currently available is the FlexConveyor by the GEBHARDT Fordertechnik company.

The illustrative programmable modules STM(M,N) can communicate with each of their four neighboring modules by sending and receiving electronic messages using a decentralized (e.g., peer-to-peer or distributed) network architecture. In other embodiments, a master-slave type architecture (where one of the modules STM(M,N) or a centralized controller communicates messages to the individual modules STM(M,N), or another type of electronic communication network or mechanism, may be used. The modules STM(M,N) are each capable of detecting an item **104** residing on top of the module and determining the item **104**'s position in the ordered sequence (via a bar code reader or radio frequency identification (RFID) tag, for example). Additionally, each module STM(M,N) is configured to determine its own position in the grid **110**. For example, once the particular arrangement of the grid **110** is set, each module's grid address (M,N) is, e.g., manually or by computer operations, input and stored in computer memory at the module. Each of the modules STM(M,N) is equipped with rollers or other conveying mechanisms, which are activated by the module's control system to move the items **104** into the grid **110**, from module to module within the grid **110** and, at the appropriate time, out of the grid **110**, as described below. An embodiment of a programmable module/smart transport module **200** is illustrated in FIG. **2**, described below.

In FIG. **1**, the programmable modules are designated as "STM(M,N)," where (M, N) refers to the row and column address of the module in the grid **110**. That is, each module in the grid **110** has a defined position in the grid as indicated by its grid address. A 3×3 grid is shown in FIG. **1** for simplicity, but the size of the grid **110** and its configuration may be adjusted as needed, e.g., according to the anticipated volume of items to be handled by the material handling system **100**. For example, to sequence one hundred items, an 11×11 grid may be constructed as shown in FIGS. **8-9**. The features of the programmable modules STM(M,N), among other things, allow the size and/or configuration of the grid **110** to be modified to sequence any number of incoming items. That is, a greater number of items can be sequenced simply by adding modules to the existing grid, and a smaller number of items can be sequenced by removing modules from the grid. In the illustrative embodiment, the grid **110** is configured for "high density" storage and sequencing, e.g., so that all of the modules in the grid **110**, except for those in the entrance row and the buffer column, are occupied with items **104** when the ordered sequence is complete.

In FIG. **1**, the entrance row of the grid **110** is illustratively shown as row **1**, and the buffer column is illustratively shown as column N. As disclosed herein, modules STM(M,N) in the entrance row and the buffer column are configured to handle items differently than the other modules in the grid **110**. Items **104** enter the grid **110** via the upper right corner module (the entrance module **108**) and travel from module to module, left or westward in the entrance row, until they reach their assigned or "target" column In the illustrative embodiment, the entrance row is used to move the items **104** to their respective target columns, but the entrance row is not used to store items in the ordered sequence. Similarly, the buffer column is used to temporarily store items **104** that would otherwise interfere with the travel of other items in the grid to their target positions. Interfering items can be moved laterally to the buffer column to get out of the way of a traveling item, and then returned to their original position once the traveling item has moved past. In other words, when all items **104** are in their proper positions, the modules STM(M,N) of the entrance row and the modules STM(M,N) of the buffer column are empty. Stated yet another way, in the illustrative embodiment, none of the items **104** should have a target address in either the entrance row or the buffer column, because the illustrative grid **110** is designed to have one additional row at the top and one additional column to the left, in addition to the number of rows and columns needed to accommodate the quantity of items sequenced by the grid **110**. In some embodiments, the system **100** is configured so that once an item **104** has reached its target position, it can only be moved laterally if it is interfering in the path of another item's travel within the grid **110**.

When the items **104** have reached their target columns in the entrance row, the modules STM(M,N) in such target column operate to move the items down or southward until the items **104** reach their target rows. To do this, rollers or other conveying mechanisms of the modules STM(M,N) are activated by the module's control system. Once the items **104** have reached their target positions in the grid **110** (e.g., the items **104** are located at both their target row and their target column), the modules STM(M,N) can move the items **104** laterally (e.g., left or right) temporarily, as needed to allow passage of other items seeking their own target positions in the grid **110**. In the illustrative embodiment, the items **104** depart the grid **110** from the bottom right corner (e.g., the exit module **108**). Accordingly, the grid **110** is designed so that the first item in the ordered sequence is moved to and stored in the bottom-right position (e.g., the exit module **108**). The subsequent items (according to the ordered sequence) are assigned and moved to corresponding target positions in the grid **110**. For instance, to sequence 100 items in an 11×11 grid such as shown in FIGS. **9-10**, items **0-9** may be placed in the right-

most column (e.g., column **1**), items **10-19** may be placed in the column to the left of the right-most column, and so on.

In the grid **110**, the modules STM(M,N) move interfering items **104** laterally (e.g., left and right) to allow the downward/southward movement of items **104** traveling to their target rows. In doing so, the interfering items **104** leave their target positions temporarily and are then returned by the modules STM(M,N) to their target positions, to maintain the ordered sequence. In the illustrative system **100**, interfering items **104** that have already moved to get out of the way of another item are not permitted to move farther away from their target position. In other words, the system **100** restricts lateral movement of interfering items **104** to one module STM(M,N) to the right or one module STM(M,N) to the left of the item **104**'s target position.

In FIG. **1**, the arrows depicted in each module of the grid **110** indicate the direction(s) in which the module can move items, and the darkened circles shown on the arrows indicate modules STM(M,N) that can store items **104** according to the ordered sequence. For example, STM(**1**,**2**), a module of the entrance row, can move items leftward/westward and southward/downward, but does not correspond to a target position in the ordered sequence. On the other hand, STM(**2**,**2**), a module in the "body" of the grid **110**, can move items **104** left/west or right/east and southward/downward, and corresponds to a target position of one of the items **104**. As such, STM(**2**,**2**) is a storage location for an item in the ordered sequence. Further, STM(**2**,N), a module of the buffer column, can receive items **104** from the right/east and move items to the right/east. While terms such as "left," "right," "up," and "down," "top," "bottom," "east," "west," "north," "south," etc., may be used herein to describe movements of the items **104** in the grid **110**, such terms are used for ease of discussion and not to limit the scope of this disclosure. Further, it should be understood that the specific examples described herein are intended for illustration purposes and not to limit the scope of the disclosure. For example, while the drawings show the entrance module **106** at the top right corner and the exit module **108** at the bottom right corner of the grid **110**, such modules may be positioned at any location in the grid **110** and the rules for item movement adjusted accordingly. Similarly, movements characterized herein as "left" or "right," "up" or "down," etc., may correspond to movements in other directions in other embodiments, in accordance with the requirements of a particular design or implementation of the system **100**.

Referring now to FIG. **2**, additional details of an embodiment of a programmable module or smart transport module **200**, which may be used in the grid **110** as the STMs (M,N), are shown. The smart transport module **200** includes an STM control system **210**, including an item sequencer module **212** and a messaging subsystem **214**. The STM control system **210**, item sequencer **212**, and messaging subsystem **214** are embodied as one or more computerized components (e.g., one or more hardware or software components, or a combination thereof) of the smart transport module **200**. The STM control system **210** is communicatively coupled to one or more data storage devices (e.g., computer memory in which a database, electronic file, table, or other computerized data structure is embodied), which stores an ordered sequence **216**, negotiation rules and departure policies **218**, and a current condition **220**. As shown in FIG. **10**, described below, the ordered sequence **216**, the rules and policies **218**, and the current condition **220** may be stored in the same data storage device, in some embodiments. In other embodiments, portions of the ordered sequence **216**, the rules and policies **218** and/or the current condition **220** may be stored in different data storage devices.

The smart transport module **200** is also communicatively coupled to an item transporter **222**, including an item detector **224**. The illustrative item transporter **222** is embodied as a mechanical or electromechanical device that can transport items from one location to another, such as a conveyor. In some embodiments, the item transporter **222** is sized specifically to correspond to the size of items to be conveyed thereby (e.g., a "unit-sized conveyor," which is designed to only hold one of the items **104** at a time). For example, the item transporter **222** may include a series or network of adjacent mechanical rollers that rotate one way to move an item **104** situated thereon in one direction, and rotate in the opposite direction to move the item **104** in the opposite direction. The axis of rotation of some rollers may be oriented perpendicularly to the axis of rotation of other rollers, to enable conveyance of items **104** in the four cardinal directions. Such rollers may be selectively turned on and off in response to control signals from the STM control system **210**, depending on the direction in which the items **104** need to move within the grid **110**.

The item detector **224** is embodied as a sensing device. For example, the item detector **224** may be embodied as a force sensor, a motion sensor, a bar code reader, an RFID transceiver, and/or others, or any combination thereof. As such, the item detector **224** detects the presence (and/or absence) of an item **104** situated on top of the item transporter **222**. In response to signals (or the lack thereof) from the item detector **224**, the STM control system **210** applies the negotiation rules and departure policies **216** to the detected current condition of the module **200**, and determines the next action to be taken by the module **200** in accordance with the ordered sequence **216**, as described further below. The detected current condition may be at least temporarily stored in computer memory, e.g., as the current condition **220**.

In addition to detecting the presence of an item **104** at the item transporter **222**, the item detector **224** identifies the detected item by reading or otherwise detecting its unique item ID **228** (which may be printed on a bar code that is attached to the item **104**, for example). In some cases, the ordered sequence **216** may be embodied as a look-up table or other type of computerized data structure, which associates or "maps" the item ID **228** with a specific target address (e.g., row and column) of the grid **110**, such that the smart transport module **200** may determine the item's target address when the item **104** arrives at the item transporter **222** based on the look-up table. In other embodiments, items **104** may arrive pre-configured with their respective target addresses. For example, each item's target address may be embodied in and read from, e.g., a bar code or other type of code or identifier that is affixed to the item **104** (by, for example, a printed label or tag).

Based on the presence or absence of an item **104** at the item transporter **222**, the STM control system **210** executes the item sequencing logic/algorithms described herein, which are embodied in the item sequencer module **212**. The item sequencer module **212** is communicatively coupled to the messaging subsystem **214**. As described in more detail below, the item sequencer module **212** communicates current condition information about the current status of the module **200** to the messaging subsystem **214** at each time step or iteration of the item sequencer **212**. In response to the current condition information, the messaging subsystem **214** issues the appropriate messages to one or more neighboring modules and/or other modules in the grid **110**, in accordance with the

negotiation rules and departure policies **218**, to effectuate the movement of the items **104** within the grid **110** from the entrance module to the target locations or addresses within the grid **110**, and then ultimately from the target locations/addresses to the exit module **108**. As used herein, "neighboring modules" may refer to, among other things, one or more smart transport modules **200** that are located in a row or column of the grid **110** that is immediately adjacent to the module **200** in question. For example, in FIG. **1**, the modules STM(**1**,**2**), STM(**2**,N), STM(**2**,**1**), and STM(M,**2**) are all neighboring modules of the module STM(**2**,**2**). As used herein, "laterally" or east-west adjacent may refer to, among other things, neighboring modules **200** that are in the same row as the module **200** in question (e.g., as to the module STM(**2**,**2**), the modules STM(**2**,N) and STM(**2**,**1**)). Similarly, "longitudinally" or north-south adjacent may refer to, among other things, neighboring modules **200** that are in the same column as the module **200** in question (e.g., as to the module STM(**2**,**2**), the modules STM(**1**,**2**) and STM(M,**2**)).

In the illustrative embodiment, each smart transport module **200** contains the same control logic (e.g., the control system **210**, ordered sequence **216**, and rules and policies **218**), and each module **200** independently decides what action to take at each time step, based on its own current condition and the current condition of one or more of its neighboring modules **200**. That is, each module **200** in the grid **110** assesses its own current condition (e.g., unoccupied, occupied by a moving item, or occupied by an item in its assigned target position), determines the current state of each of its neighboring modules, enters two rounds of sequencing logic referred to herein as "negotiations," in order to determine whether or not the module **200** will convey an item to another module **200** in the current time step or iteration, and, if the module **200** is to convey an item **104**, the direction in which direction such item **104** is to be conveyed. In other embodiments, however, a centralized controller may be communicatively coupled to the messaging subsystem **214**, such that it may execute the control logic and communicate instructions to the individual control modules **200** accordingly.

To form the grid **110**, the requisite number of modules **200** are communicatively and mechanically connected to their neighboring modules **200** so as to be able to communicate with one another via electronic messages or signals and to be able to pass items **104** from one module **200** to adjacent modules **200**. The communicative connections may be wired or wireless electronic connections, and may be accomplished by, for example, connecting communication ports of the modules **200** via cables. The mechanical connections may be accomplished by any suitable type of mechanical coupler or fastener, such as a bracket, tether, or connector. Once all modules **200** are communicatively connected in the grid **110**, each module **200** is assigned its address, e.g., the row and column number corresponding to its position in the grid **110**. Knowledge of its own address within the grid **110** enables each module **200** to assess its current condition in the event an item **104** is detected thereon. For example, a module **200** can compare its own grid address to the target address of an item **104** that is detected by the item detector **224**, and determine based on such comparison whether the item **104** has reached its target address or needs to be moved to another module **200** in the grid **110**.

Referring now to FIG. **3**, illustrative subcomponents of the item sequencer **212** are shown, including a module current condition check subcomponent **310**, a check departure policy subcomponent **312**, entrance row logic **314**, item seeking negotiation logic **316**, interfering item negotiation logic **318**, and an execute convey subcomponent **320**. These subcomponents are embodied as one or more computerized components (e.g., one or more hardware or software components, or a combination thereof) of the item sequencer **212**. In operation, the illustrative item sequencer **212** iterates through the sequence of subcomponents in each time interval of operation. Additionally, the item sequencer **212** executes the same subcomponent at the same time for all of the modules **200** in the grid **110**. In other words, the modules **200** in the grid **110** are synchronized to operate in the same "phase" at the same time. Except for the modules **200** of the entrance row, all of the modules **200** are executing the same subcomponent of the item sequencer **212** at any given time step. However, some of the modules **200** in the grid **110** may behave differently than other modules, even though they are executing the same subcomponent at the same time. For example, depending on the module **200**'s current condition, a module may send a message to other modules **200**, propagate a message that it has received from another module **200**, affirmatively not send a message to other modules **200**, or affirmatively not propagate a message received from another module **200**.

When the item sequencer **212** is executing the current condition check **310**, each of the modules **200** in the grid **110** determines if it is occupied (e.g., checks whether the item detector **224** detects the presence of an item **104**), and updates its current condition accordingly. The module **200** stores the current condition information temporarily (e.g., in a cache memory) or until no longer needed (e.g., until it is supplanted by a new current condition at a subsequent next time interval). In the illustrative embodiment, there are three possible values for the module current condition: "empty," "occupied," and "seeking" (where empty=no item detected, occupied=item detected and item is at its target position and seeking=item detected and item is not yet at its target position). The module **200** determines its current condition by reading the item id **228** (e.g., from an RFID tag or a bar code) and comparing the item's target position in the grid **110** to the module's own position in the grid **110**, as mentioned above.

Once the item sequencer **212** has determined the module **200**'s current condition for all of the modules in the grid **110**, the check departure policy **312** is executed. During the check departure policy **312**, each module **200** checks to see if it meets a "departure condition," meaning that the module **200** checks to see if the ordered sequence is complete and the items **104** are ready to leave the grid **110**. There are a number of different departure policies that may be used, each of which may have different departure conditions. The departure policy applicable to the grid **110** may be selected based on the requirements or the design of the automated material handling system **100**, and/or other requirements or criteria.

In one example, a first departure policy requires that all of the items **104** in the ordered sequence **216** be in the grid **110** and sequenced before any items leave. In this case, the module **200** sends messages to its north and west neighboring modules, to see if those modules **200** are carrying their respective assigned items **104** in accordance with the ordered sequence **216**. If all of the items **104** in the grid **110** meet this condition, then all of the modules **200** in the grid **110** are considered to meet the departure condition. As another example, a second departure policy requires that (1) all modules in a particular column in the grid **110** are carrying their required items and (2) all columns to the right have met the departure condition. In both cases, if a module meets the departure condition, it no longer executes the negotiating events to follow. Additional details of the exemplary departure policies are described below with reference to FIG. **5**. The departure policies are typically pre-defined and stored as,

for example, computer-readable data, rules, or instructions (e.g., Boolean logic implemented in a computer programming language), in, for instance, the rules and departure policies **218**.

In the illustrative example, the item sequencer **212** executes the entrance row logic **314** and the item seeking negotiation **316** during the same phase of the iteration, but the entrance row logic **314** is only executed by modules **200** that are located in the entrance row while the item seeking negotiation **316** is executed by all of the other modules **200** in the grid **110**. The entrance row logic **314** controls the movement of items **104** in the entrance row **314**, while the item seeking negotiation **316** controls the movement of items **104** that are in their respective target columns but still need to move to their target row. An embodiment of the entrance row logic **314** is described in more detail below with reference to FIG. **4**. An embodiment of the item seeking negotiation **316** is described in more detail below with reference to FIG. **6**.

Following completion of the item seeking negotiation **316** by all of the modules **200**, the item sequencer **212** executes the interfering item negotiation **318** to handle the movement of interfering items out of the way of other "seeking" items **104** in the grid **110**. An embodiment of the interfering item negotiation **318** is described in more detail below with reference to FIG. **7**.

After execution of all of the foregoing modules **310**, **312**, **314**, **316**, **318**, the item sequencer **212** enters a convey phase in which the execute convey **320** communicates with the item transporter **222** to execute the movement decisions in accordance with the updated current condition of each of the modules **200** in the grid **110**. In some embodiments, negotiation rules **218** are established such that the final condition of a module **200** cannot be a "request" condition (e.g., request left, request right, etc.). After the execute convey **320**, the item sequencer **212** increments the time interval and begins the new time interval by returning to the module current condition check **310** and repeating the process described above. The item sequencer **212** repeats the above process for as many time intervals or "time steps" as are needed to complete the storage of items **104** in the ordered sequence **216** and convey the ordered items **104** out of the grid **110**. For example, the item sequencer **212** may conclude its execution if there are no items **104** detected by any of the modules **200** in the grid **110**.

Referring now to FIG. **4**, an illustrative method **400** by which the automated material handling system **100** may handle incoming items, e.g., items **104** in the entrance row of the grid **110**, is shown. The method **400** may be embodied as computerized programs, routines, logic and/or instructions executed by the system **100**, for example by the item sequencer **212** of the smart transport modules **200**. In the illustrative embodiment, all of the modules **200** in the grid **110** may execute the method **400** synchronously.

As noted above, the entrance row of the grid **110** handles items **104** differently than other parts of the grid **110**. At block **410**, the system **100** initiates execution of the method **400** by the modules **200** that are located in the entrance row of the grid. Other modules **200** in the grid **110** may execute the item seeking negotiation logic **316** during the same time interval in which the entrance row modules **200** are executing the method **400**. The system **100** may begin the method **400** upon successful completion of the execution of the check departure policy **312**, for example.

At block **412**, the entrance row modules **200** activate their respective item transporters **220** to move the incoming items **104** to their respective target columns, within the entrance row. To do this, the entrance row modules **200** each determine whether they are carrying an item **104** (by, e.g., the item detector **224**). If an entrance row module **200** is carrying an item **104**, the module **200** compares the target column information of the carried item **104** to the module **200**'s own assigned column number (e.g., the module **200**'s column address in the grid **110**). At block **414**, the module **200** determines whether the carried item **104** is at its assigned target column based on the comparison performed at block **412**. If the target column of the carried item **104** matches the carrying module **200**'s own column address, the module **200** concludes that the item **104** is at its target column and proceeds to block **420**, at which no action is taken because the carried item **104** does not need to be moved to another column. If the target column of the carried item **104** does not match the carrying module **200**'s own column address, the module **200** concludes that the item **104** has not yet reached its target column and needs to continue movement leftward/westward in the entrance row of the grid **110** It should be understood that the direction of movement is leftward/westward because in the illustrative embodiment, items **104** enter the grid **110** at the right-most module **200** of the entrance row, and that the movement may occur in other directions in other embodiments. At block **416**, the module **200** carrying the item **104** that needs to move westward sends a "request left" message to all of the modules **200** that are to the left or westward of the carrying module **200** in the entrance row of the grid **110**. All other modules **200** that are carrying items **104** in the entrance row that need to move westward also send "request left" messages to the westward modules **200**, similarly. The westward modules **200** that receive the request left messages do not respond unless their current condition is "empty." In other words, the only modules **200** that respond to the request left messages are modules **200** that are not currently carrying an item **104**. The empty modules **200** respond to the request left message by sending a "committed left" message back to the module **200** that initiated the request left message, through any intervening modules **200** that are located in between the empty module **200** and the request left initiating module **200** (e.g., the intervening modules **200** each propagate the message originally sent by the empty module **200** eastward toward the request left initiating module **200**).

At block **418**, the request left initiating module **200** determines whether it has received a committed left response message. If the request left initiating module **200** does not receive a committed left response, the request left initiating module **200** concludes that there are no empty modules westward in the entrance row, and thus westward movement is not currently possible. As a result, the method **400** proceeds to block **420** and takes no action. If, however, the request left initiating module **200** receives a committed left response, the request left initiating module **200** updates its current condition to "committed left" to indicate that it will move its item **104** to the leftward adjacent module **200** when it is time for item movements to occur (e.g., during the execute convey phase **320**). Thus, in the method **400**, there are two "waves" of messages generated by modules **200** in the entrance row: the leftward/westward request left messages sent by the request left initiating modules **200** and the rightward/eastward committed left messages sent in reply by the empty modules **200** in the entrance row. At block **424**, the leftward movement of items **104** in the entrance row is executed by all of the modules **200** in the entrance row that have a current condition of "commit left" (e.g., all of the modules **200** that are between the empty module **200** and the request left initiating module **200**, and including the request left initiating module **200**. To do this, each of the modules **200** activates the conveying mechanism (e.g., rollers) of its respective item transporter **222** to move the items **104** in the westward direction. The

movement of the items **104** is conducted by the entrance row modules **200** synchronously, resulting in a "block movement" of items **104** to the left in the entrance row.

Referring now to FIG. **5**, an illustrative method **500** by which the automated material handling system **100** may handle the departure of items **104** from the grid **110** is shown. The method **500** may be embodied as computerized programs, routines, logic and/or instructions executed by the system **100**, for example by the item sequencer **212** of the smart transport modules **200**. In the illustrative embodiment, all of the modules **200** in the grid **110** may execute the method **500** synchronously.

At block **510**, the system **100** initiates execution of the method **500** by the modules **200** of the grid **110**. The system **100** may begin the method **500** upon successful completion of the execution of the module current condition check **310**, for example. At block **512**, the system **100** determines the applicable departure policy. Disclosed herein are two illustrative departure policies that may be implemented alternatively by the system **100**: a "column leave when sequence ready" policy and a "column leave when column ready" policy. According to the column leave when sequence ready policy, a column of items **104** is ready for departure from the grid **110** when all of the column's member items **104** are in their respective target positions according to the ordered sequence, and all of the items **104** of the preceding columns in the grid **110** have already departed from the grid **110** (where "preceding columns" refers to items **104** that are in the columns between the column of the exit module **108** and the column currently being evaluated, and includes the column of the exit module **108**). Other suitable departure policies may be used. However, in general, all departure policies provide that items **104** may depart from the grid **110** only when their predecessor items **104** (e.g., the preceding items according to the ordered sequence) are in their respective target locations in the grid **110** (e.g., to effectuate the ordered sequence of items **104**). The departure policies are stored in computer memory, e.g., in the rules and policies **218**.

At block **514**, the system **100** determines whether the applicable departure policy is "depart when column ready." If the system **100** concludes that the departure policy is not depart when column ready, the illustrative system **100** assumes that the departure policy is "depart when sequence ready" and proceeds to block **516**. At block **516**, the system **100** checks to see if all of the items **104** in the preceding portions of the grid **110** are in their respective target locations (e.g., whether the ordered sequence is complete for the entire grid **110**). If at block **520** the system **100** concludes that all of the items **104** in the grid **110** are ready to depart the grid **110**, the system proceeds to block **526**. If at block **520** the system **100** concludes that all of the items **104** in the grid **110** are not ready to depart the grid **110**, the system **100** proceeds to block **524**, where no action is taken.

If at block **514** the system **100** determines that the applicable departure policy is "depart when column ready," the system **100** proceeds to block **518**, where it checks the ordered sequence column by column That is, each column of the grid **110** is checked individually to see if all of the modules **200** in the column are "occupied;" that is, carrying an item **104** that is in its target position. At block **522**, the system **100** determines whether the column currently being checked for departure readiness is ready to depart, based on the criteria evaluated at block **518**. If the system **100** determines that the column is not ready to depart (e.g., all modules **200** in the column are not occupied with items **104** in their target positions), the system **100** proceeds to block **524** and takes no action. If the system **100** determines that the column is ready to depart (e.g., all modules **200** in the column are occupied with items **104** in their target positions), the system **100** proceeds to block **526**. At block **526**, the items **104** in the grid **110** are moved (e.g., rightward/eastward) column-by-column to the column in which the exit module **108** is located ("departure column"), and then moved (e.g., downward/southward) to the exit module **108** and out of the grid **110**. The movement of the items **104** is conducted by the modules **200** synchronously, resulting in block movements of the columns of items **104** to the departure column and then out of the grid **110**. To accomplish such movements, each module **200** activates the conveying mechanism (e.g., rollers) of its respective item transporter **222**. At block **528**, the system **100** checks to see if there is another column of items **104** in the grid **110** that may be ready to depart. If the system **100** concludes that there is another column of items **104** in the grid, the system returns to block **518** and proceeds to evaluate the column as described above. If the system **100** determines that there are no other columns of items **104** left in the grid **110**, the system **100** proceeds to block **530** and takes no action.

To check the ordered sequence for departure readiness, the system **100** (e.g., the messaging subsystem **214**) initiates message passing from the exit module **108** to the other modules **200** in the grid **110**. In the illustrated embodiment, since the exit module **108** is located at the bottom right-most position of the grid **110**, the departure readiness messages originate at the exit module **108** and propagate module-to-module to the north and west of the exit module **108** all the way out to the modules **200** that are furthest away from the exit module **108** in all directions. The modules **200** in the rightmost column will forward the messages both north and west, depending on the current condition of the respective module **200**. That is, when a departure readiness message is received by a module **200**, the receiving module **200** determines if it is carrying an item **104** that is in its target position as described above. If the receiving module **200** is not carrying an item **104** at all or is carrying an item that is not in its target position, the receiving module **200** will not forward the departure readiness message on to other modules **200** and the message propagation will end. If the receiving module **200** is carrying an item **104** that is in its target position, the receiving module **200** will continue the propagation of the departure readiness message across the grid **110**. If the departure readiness message reaches the modules **200** in the grid that are the farthest away from the exit module **108** in all directions, the modules **200** return the message in the opposite direction as a "sequence ready" message. The modules **200** that are located in between the outermost modules in the grid **110** and the exit module **108** propagate the sequence ready message back to the exit module **108**, module by module. Thus, if the exit module **108** receives a sequence ready message, the system **100** knows that the items **104** in the grid **110** (or a portion thereof, depending on the departure policy) are ready for departure from the grid **110**.

After receiving the sequence ready message, the exit module **108** (which, in the illustrative embodiment, stores the first item **104** in the ordered sequence) broadcasts another message to initiate the movement of items **104** out of the grid **110** ("departure movement"). To do this, the exit module **108** sends out a message to its adjacent north neighboring module **200**, and the north neighboring module **200** continues the propagation of the departure movement message to all of the modules **200** that are in the same column as the exit module **108** and the north neighboring module **200**. When the last module **200** in the column receives the departure movement message, it responds with a "commit down" movement message, which is propagated by the other modules **200** in the

column back to the exit module **108**. When the exit module **108** has received the commit down message, the system initiates the movement of the items **104** out of the grid **110**.

When the exit module **108** detects that it is empty (not currently carrying an item **104**), the exit module **108** sends a message to its west neighboring module **200** to move the next column of items **104** into position for departure. In the same way, the west neighboring module **200** that receives this message sends a message to its north neighboring module **200**, which then triggers the movement of all of the items in the column of the west neighboring module **200** into position for departure (e.g., to the right/east).

If portions of the ordered sequence are complete when items **104** start to depart the grid **110**, the system **100** can move those portions toward the departure position (e.g., eastward) as a block. In this case, the system **100** may move other columns of items **104** to the right (toward the departure position) so that they are ready for departure. Further, to accomplish a block movement toward the departure position, each module **200** sends a message leftward, which propagates to the leftmost module **200** in the grid **110** that is carrying an item **104**.

Depending on the departure policy, the system **100** may check the readiness of the ordered sequence in a particular column If the departure policy is "depart when the column is ready," all columns are not always ready even if the departure has already started. As a result, there may be two additional message passing rounds in order to verify that the ordered sequence is correctly ordered and ready for departure, where the first round is initiated at the exit module **108** to determine whether the modules **200** are occupied with items **104** that are in their target positions, and the second round is the feedback from the modules **200** responding to the "departure ready message."

An embodiment of the "depart when sequence is ready" departure policy specifies that items **104** may leave the grid **110** only after the entire ordered sequence (e.g., the entire grid **110**) is ready. In the illustrated embodiment, the first item in the ordered sequence (and thus the first item **104** to leave the grid **110**) is located at the bottom right position (the exit module **108**). Therefore, whenever the first item **104** in the ordered sequence arrives at its target position, the module **200** carrying the item **104** triggers a sequence check mechanism and sends messages to the other modules **200** in the grid **110**, in both north and west directions. In this way, messages propagate all across the grid **110**, and when the left-most modules **200** (farthest away from the exit module **108**) receive the message, they send a reply message, which is propagated back to the exit module **108**. If a module **200** is empty or is not occupied with an item that is in its target position, the module **200** does not respond to the incoming message. In this way, the message becomes interrupted and the item departure does not start. If the message returns to the exit module **108**, the exit module **108** knows that the entire sequence is ready and items can start to leave the grid **110**.

In an embodiment of the "depart when column ready" departure policy, items **104** start to leave when their assigned column and all of the predecessor columns are ready to depart. In some cases, the system **100** permits items **104** to depart as soon as their predecessors are in their target positions according to the ordered sequence. In such event, the exit module **108** (e.g., the bottom right module) initiates the messages that are sent out to the other modules **200** in the grid **110**. In response, each of the other modules **200** checks to see if its own row and column address matches the target row and column address of the item **104** that is currently being carried by the module **200**. However, in this case, the module **200** propagates the message only to its north neighboring module **200** and not to any westward modules **200**. This message propagates and returns from the row that is furthest away from the message sending module **200** (e.g., the top row of the grid **110**), if all items **104** are in their target positions in the column of the message sending module **200**. If the message sending module **200** receives the response message, it forwards the message to its adjacent west neighboring module **200**, and the west neighboring module triggers a similar sequence check in its own column by sending a message to its adjacent north neighboring module **200**.

Further, in an embodiment of the "depart when column ready" departure policy, the message route begins at the exit module **108** (e.g., the bottom right module **200**), and a separate sequence check is done for each column When a column's sequence is ready to depart the grid **110**, the exit module **108** forwards the message to the next adjacent west neighboring module **200** for additional subsequent sequence checks. If any module **200**'s row and column number does not match with the target row and column of the item **104** that it is currently carrying, the message passing stops and departure cannot start for the specified column

After the message passing for the sequence check (which verifies that items **104** are in their target positions according to the ordered sequence), if the exit module **108** determines that the sequence is ready for the entire grid **110** or for a particular column (depending on the departure policy) to depart, the exit module **108** starts a negotiation similar to the item seeking or north-south negotiation described below. The exit module **108** will send out a message to its adjacent south neighboring module **200**, and if the south neighboring module **200** is empty, the south neighboring module **200** moves its item **104** to the exit module **108** for departure from the grid **110**. Additionally, the south neighboring module **200** forwards the message to its adjacent north neighboring module **200**. In this way, the modules **200** in the column can execute a block movement to the south. To accomplish such movements of items **104**, each module **200** involved in the movement activates the convey mechanism (e.g., rollers) of its respective item transporter **222**).

When the items **104** in the first column have departed the grid **110** entirely, the exit module **108** detects that it is empty and sends a message to its adjacent west neighboring module **200**. This message initiates a block move of the items **104** from left to right, which is similar to the interfering item (e.g., west-east) negotiation, described below, except that in this case, there are two waves of messages. To accomplish such movements of items **104**, each module **200** involved in the movement activates the convey mechanism (e.g., rollers) of its respective item transporter **222**).

Referring now to FIG. **6**, an illustrative method **600** by which the automated material handling system **100** may conduct an "item seeking" (e.g., north-south) negotiation, for the movement of items **104** within the grid **110**, is shown. The method **600** may be embodied as computerized programs, routines, logic and/or instructions executed by the system **100**, for example by the item sequencer **212** of the smart transport modules **200**. In the illustrative embodiment, all of the modules **200** in the grid **110** may execute the method **600** synchronously.

At block **610**, the system **100** initiates execution of the method **600** by the modules **200** of the grid **110**. The system **100** may begin the method **600** upon successful completion of the execution of the check departure policy **312**, for example. More specifically, the method **600** deals with items **104** that have already reached their target column (e.g., via the entrance row logic **314**), but have not yet reached their target

row. At block **612**, each "seeking" module **200** (a module that is currently carrying an item **104** that is not yet in its target position in the grid **110**, according to the ordered sequence) sends a message to its adjacent south neighboring module **200** to determine whether the south neighboring module **200** is empty (e.g., not currently carrying an item). At block **614**, the system **100** determines whether the south neighboring module **200** is empty (e.g., via the item detector **224** detecting the presence of an item **104**). If the system **100** determines that the south neighboring module **200** is empty, then at block **616** the south neighboring module **200** responds with a message indicating that it is committed to receive and the item seeking module **200** sets its current condition to "convey down." At block **618**, during the execute convey phase **320**, all modules **200** having a condition of "convey down" activate their respective item transporters **220** to move their items **104** to their adjacent south neighboring module **200**. Where the item sequencer **212** proceeds to the interfering item negotiation **318** as the next phase, modules **200** that have a current condition of "convey down" will take no action during the interfering item negotiation **318** and simply wait for the execute convey phase **320** to begin.

If, at block **614** the system **100** determines that the south neighboring module **200** is not empty, at block **620** the south neighboring module **200** sets its current condition to "request left or request right" so that when the interfering item negotiation **318** begins, the south neighboring module **200** will execute the interfering item logic described below. At block **622**, no action is taken, other than the system **100** waits for all of the modules **200** in the grid **110** to complete the item seeking negotiation logic **316** (or the entrance row logic **314**, for modules **200** located in the entrance row), before proceeding to the interfering item negotiation **318**. In other words, the item seeking or north-south negotiation places each module **200** in a beginning state for the interfering item or east-west negotiation to follow. For example, when a module **200** with an occupied (but not moving) item **104** receives a message from its north neighboring module **200** that the north neighboring module **200** wants to send its item **104** southward, the module **200** receiving such message sets its current condition to "request left or right" for the interfering item negotiation **318**.

Referring now to FIG. **7**, an illustrative method **700** by which the automated material handling system **100** may conduct an "interfering item" (e.g., east-west) negotiation, is shown. The method **700** may be embodied as computerized programs, routines, logic and/or instructions executed by the system **100**, for example by the item sequencer **212** of the smart transport modules **200**. In the illustrative embodiment, all of the modules **200** in the grid **110** may execute the method **700** synchronously.

At block **710**, the system **100** initiates execution of the method **700** by the modules **200** of the grid **110**. The system **100** may begin the method **700** upon successful completion of the execution of the item seeking negotiation **316**, for example. In general, the item seeking or east-west negotiation attempts to clear the way for items **104** that are in their target column and need to move downward to their target rows. At block **712**, the modules **200** that have a current condition of "request left or right" send messages to their respective laterally adjacent (e.g., left and right) neighboring modules **200**, to determine whether either of such modules can receive an item **104** passed in the appropriate direction. If the modules **200** receiving the request left or right message are not empty, such modules **200** propagate the request left or request right message laterally (e.g., left and right) until an empty module **200** is found in the same row. If an empty module **200** is found (block **714**), then at block **716**, the empty module **200** responds to the request left or right message with a "willing" message indicating that it can receive an item **104**. At block **718**, all of the intervening modules **200** between the module **200** issuing the request left or right message and the empty module **200** commit to convey their respective carried items **104** in a block movement (where all of the committed modules **200** move their items **104** in the same direction at substantially the same time). At block **720**, the module issuing the request left or right message receives the willing message responses and makes a decision to move based on the first-received willing message. In other words, if modules **200** on both lateral sides of the requesting module **200** respond "willing," the requesting module **200** commits to move its item **104** in the direction of the first-to-respond willing module **200**. The requesting module **200** sends a commit message to the modules **200** that are between it and the first-to-respond willing module **200**. In other embodiments, of course, the requesting module **200** may use other criteria for determining which of multiple willing modules to select. At block **722**, the block movement in the direction of the selected willing module is executed. To do this, the modules **200** involved in the movement activate their respective item transporters **222**.

In the illustrative embodiment, no movement of items **104** occurs until the interfering item negotiation **318** is complete. In other words, all of the subcomponents shown in FIG. **3** execute to determine the current condition of each of the modules **200** at a given time step, and then movement of all of the modules **200** occurs during the execute convey phase **320**, based on the current condition of each of the modules **200**. Thus, in the illustrative embodiment, at the end of the item seeking or east-west negotiation, all of the modules **200** in the grid **110** are committed to move left or right (if they are an interfering module), down (if they are a seeking module), or to remain idle (if they are occupied and not interfering).

In some embodiments, lateral movement of the items **104** in the grid **110** is temporary and restricted to one position away from the item's current position. Since, as a result of the entrance row logic, items **104** that are permitted to move laterally are ones that already have arrived at their target column, the lateral movement of such items is temporary and restricted so that the ordered sequence is preserved. Further, after a lateral move, a module **200** that has received a new item **104** from a lateral direction (e.g. left or right) detects that the item has a target column that is different (e.g., smaller or larger) than its own column number. As a result, such module **200** sends a request left or right message to the lateral neighboring module **200** having the same column number as the interfering item **104** moved by the lateral move (e.g., the module **200** from which the item **104** was received). Therefore, modules **200** that receive interfering items **104** initiate request messages to move the received items **104** back to their target positions in the next iteration. The buffer column described above is used during the interfering item negotiation to allow for lateral movements of items **104** even in rows of the grid **110** that have all of their modules **200** occupied.

In FIG. **8**, a snapshot graphic of an exemplary grid **800** is shown. The grid **800** is an 11×11 grid with an entrance row **810**, a buffer column **812**, and a number of modules **814** (e.g., the smart transport modules **200**), including an entrance module **816** and an exit module **818**. The grid **800** is populated with a number of items **104**, each of which is identified by an item ID **228** which is, in this case, a unique sequential number that corresponds to the item's target position according to the ordered sequence. During the illustrated time interval, items **44** and **60** are in the grid **800** and traveling downward to their target rows. Item **60** will ultimately travel to the bottom row.

Items **67** and **68** have been moved to the left to allow item **60** to pass by. Item **48** is moved to the left to allow the passage of item **44**. Item **88** is traveling westward to its target column in the entrance row **810**.

In FIG. **9**, another snapshot graphic of the exemplary grid **800** is shown at a later point in time than the snapshot of FIG. **8**. In FIG. **9**, the modules **200** of the gird **800** are executing a "depart when column ready" departure policy. The items **104** in the first column of the grid **800** are leaving from the exit module **818**. The items **41**, **10**, and **53** are still in transit to their target positions. In FIG. **9**, it can be seen that the ordered sequence is nearly complete, whereas in FIG. **8**, many of the items **104** are still out of sequence.

IMPLEMENTATION EXAMPLES

Aspects of the system **100** can resolve item sequencing problems in, among other applications, automated distribution systems, such as robotic and other mixed pallet building systems. Some aspects of the system **100** are applicable to, among other things, item handling and distribution environments that have both high throughput and high space utilization requirements. Aspects of the system **100** can be used in other applications as well, including sequencing outbound loads on a shipping dock for last-in, first-out delivery and sequencing parts and subassemblies in automotive manufacturing. The disclosed methods are applicable to very high-density grids that rely on "puzzle-based movement" of items in the grid, where the grid is made up of unit-sized conveyor modules. Further, embodiments of the system **100** can be implemented at different aspect ratios and multiple scales. For example, control of the modules **200** can be decentralized, which increases the scalability and reliability of the system **100**.

Referring now to FIG. **10**, a simplified block diagram of an exemplary environment **1000** in which aspects of the illustrative material handling system **100** may be implemented is shown. While the environment **1000** is shown as involving multiple components and devices, it should be understood that in some embodiments, the system **100** may constitute a single computing device, alone or in combination with other devices.

The illustrative material handling system **100** includes a computing device **1010**, which may be in communication with one or more other computing systems or devices **1040** via one or more networks **1030**. For example, in some embodiments, the computing devices **1010**, **1040** embody the smart transport modules **200** in a decentralized, peer-based network. In other embodiments, the computing devices **1010**, **1040** may represent a master-slave type architecture in which, for example, the computing device **1010** embodies a smart transport module **200** and the computing device **1040** embodies a master controller that controls the behavior of the smart transport module **200** and other modules **200** in the grid **110**.

The illustrative computing device **1010** includes at least one processor **1012** (e.g. a microprocessor, microcontroller, digital signal processor, etc.), memory **1014**, and an input/output (I/O) subsystem **1016**. The computing device **1010** is embodied as a smart transport module **200** but may be embodied as any type of computing device such as a desktop, laptop, tablet, a server, enterprise computer system, a network of computers, a combination of computers and other electronic devices, or other electronic devices.

Although not specifically shown, it should be understood that the I/O subsystem **1016** typically includes, among other things, an I/O controller, a memory controller, and one or more I/O ports. The processor **1012** and the I/O subsystem **1016** are communicatively coupled to the memory **1014**. The memory **1014** may be embodied as any type of suitable computer memory device (e.g., volatile memory such as various forms of random access memory).

The I/O subsystem **1016** is communicatively coupled to a number of hardware and/or software components and/or other computing systems including data storage **1018**, a user interface subsystem **1020** (which may include, for example, one or more user input and output devices such as a touch-screen, keyboard, virtual keypad, microphone, speakers, displays, LEDs, etc.), and a communication subsystem **1022**, in addition to an item detector **220**A, STM control system **210**A, and item transporter **220**A. It should be understood that each of the foregoing components and/or systems may be integrated with the computing device **1010** or may be a separate component or system that is in communication with the I/O subsystem **1016** (e.g., over a network). For instance, the item transporter **220**A may be embodied as a separate system.

The data storage **1018** may include one or more hard drives or other persistent data storage devices (e.g., flash memory, memory cards, memory sticks, and/or others). The ordered sequence **216**A, rules and polices **218**A, and current condition **220**A constitute data elements that may be stored, at least temporarily, in the data storage **1018**. In some embodiments, portions of systems software (e.g., an operating system, etc.), framework/middleware (e.g., application-programming interfaces, object libraries, etc.), The communication subsystem **1022** communicatively couples the computing device **1010** to the network **1030**, which may be embodied as one or more networks, e.g., a local area network, wide area network, personal cloud, enterprise cloud, public cloud, and/or the Internet, for example. Accordingly, the communication subsystem **1022** may include one or more wired or wireless network interface software, hardware, or combination thereof, as may be needed pursuant to the specifications and/or design of the particular computing device **1010**.

The computing device **1040** may be embodied as any suitable type of computing device such as any of the aforementioned types of devices or other electronic devices, in a similar manner as the computing device **1010**. As such, components of the computing device **1040** having the same or similar names as the components of the computing device **101** are embodied similarly, and the description is not repeated here for brevity. Similarly, the components of the computing devices **1010**, **1040** that correspond in name to components of the smart transport module **200** described above are embodied similarly, and therefore the description is not repeated here. In embodiments in which the computing devices **1010**, **1040** represent two peer smart transport modules **200** of the grid **110**, the components **210**A, **216**A, **218**A, **222**A, **224**A represent the components of one of the smart transport modules **200** and the components **210**B, **216**B, **218**B, **222**B, **224**B represent the components of the other of the smart transport modules **200**. In master-slave type embodiments, the components **210**A, **216**A, **218**A, **222**A, **224**A may represent local portions or copies of the system **100** while the components **210**B, **216**B, **218**B, **222**B, **224**B may represent remote or server-based components of the system **100**.

The computing system **1000** may include other components, sub-components, and devices not illustrated in FIG. **10** for clarity of the description. In general, the components of the computing system **1000** are communicatively coupled as shown in FIG. **10** by signal paths, which may be embodied as any type of wired or wireless signal paths capable of facilitating communication between the respective devices and components.

ADDITIONAL EXAMPLES

In at least one example, the present disclosure provides a method for arranging in an ordered sequence a number of physical items randomly presented to an automated material handling system having a plurality of programmable modules arranged in a grid, where each of the programmable modules can at least temporarily store one of the items at a time and transfer the stored item to an neighboring module in an automated fashion, and where the grid includes a plurality of rows in which items may travel bi-directionally and a plurality of columns in which items may travel bi-directionally. The method includes, with the programmable modules: admitting an item to the grid at a module of an entrance row of the grid; determining a current address of the module at which the item is currently located in the entrance row, the current address defined by a row identifier and a column identifier; determining a target address of a module at which the item is to be temporarily stored according to the ordered sequence, the target address defined by a row identifier and a column identifier; determining if the column identifier of the current address corresponds to the column identifier of the target address; if the column identifier of the current address does not correspond to the column identifier of the target address, activating a transport mechanism of one or more of the modules in the entrance row to move the item within the entrance row to the column of the target address; if the column identifier of the current address corresponds to the column identifier of the target address, determining if the row identifier of the current address corresponds to the row identifier of the target address, and if the row identifier of the current address does not correspond to the row of the target address, determining a new address, the new address having a column identifier that corresponds to the column of the current address and the new address being closer in proximity to the target address than the current address; and if another item is interfering with movement of the item to the new address, activating a transport mechanism of one or more of the modules in the row of the new address to temporarily move the interfering item to another module in the same row as the new address and activating a transport mechanism of one or more of the modules in the column of the new address to move the item to the new address.

The method may include, at each module of the entrance row, determining if the module is carrying an item and if the module is carrying an item, determining if the item is located at its target address. The method may include, by the module receiving the item admitted to the entrance row of the grid, initiating a message to another module in the entrance row to request movement of the item to another column in the entrance row. The method may include, by the module receiving the message, propagating the message to another module in the entrance row. The method may include, by the module receiving the message, sending a return message to the module receiving the item admitted to the entrance row of the grid, wherein the return message indicates that the module receiving the message can accommodate the movement of the item to another column in the entrance row. The method may include, in response to the return message, activating the transport mechanism of at least the module sending the return message and the module receiving the item admitted to the entrance row to move the item to another column of the entrance row that is closer to the column of the target address than the column of the current address. The method may include activating the transport mechanism of each of the modules between the module sending the return message and the module receiving the item admitted to the entrance row to move each of the items located in the entrance row to another column of the entrance row.

In at least one example, the present disclosure provides a system for arranging a number of randomly presented physical items in an ordered sequence to be handled by a robot, where the system includes programmable modules arranged in a grid, where each of the programmable modules can at least temporarily store one of the physical items, transfer the stored item to a neighboring module, and communicate messages to other modules in the grid. The system is to determine a target module at which the item is to be temporarily stored according to the ordered sequence, where the target module has an address defined by a row and a column; admit an item at a module of an entrance row of the grid, move the item within the entrance row to the column of the target module; move the item within the column of the target module to the row of the target module; and move an item that interferes with the moving of the item toward the target module from its target position to a buffer column of the grid, the buffer column operable to temporarily store items that interfere with the movement of the item traveling toward the target module.

The system may, by a module carrying the interfering item, initiate a message to other modules in the same row as the interfering item to request movement of the interfering item to the buffer column The system may, by an empty module in the buffer column in the same row as the interfering item, send a return message to the module carrying the interfering item indicating that the empty module can assist with the movement of the interfering item. The system may activate the transport mechanisms of at least the module carrying the interfering item and the empty module to move the interfering item to the empty module. The system may, in response to determining that the interfering item is no longer interfering with the movement of the item traveling toward the target module, activate the transport mechanisms of at least the empty module and the module carrying the interfering item to return the interfering item to its target position. The system may receive return messages from a plurality of empty modules in the same row as the module carrying the interfering item and select a first to respond empty module of the plurality of empty modules to assist with the movement of the interfering item. The system may initiate movement of the interfering item in the direction of the selected empty module.

In at least one example, the present disclosure provides a programmable module that includes a transport mechanism and a computer component embodying control logic to control the operation of the transport mechanism, where the transport mechanism operable to at least temporarily store a physical item and transfer the item to a neighboring module in a grid of programmable modules, the position of each of the programmable modules in the grid is defined by a row and a column, the computer component is operable to communicate messages to other modules in the grid, and the grid of programmable modules is operable to arrange a number of randomly presented items to exit the grid in an ordered sequence. The control logic of the programmable module is to determine a current condition of the programmable module as one of empty, occupied, or seeking, where empty indicates that the programmable module is not currently storing an item, occupied indicates that the programmable module is storing an item that is in a target position defined for the item in accordance with the ordered sequence, and seeking indicates that the programmable module is currently storing an item that has not reached its target position. The control logic is also to determine if the current condition of the programmable module satisfies a departure policy, where the depar-

ture policy is satisfied if (a) all modules in the same column as the programmable module and all modules in all columns between the column of the programmable module and an exit column from which items exit the grid, including the exit column, have a state of occupied or (b) all items to be sequenced are in the grid and at their target positions. The control logic is also to initiate a message to one or more neighboring modules in the same row or column as the programmable module to determine if the neighboring modules can receive an item currently stored by the programmable module, receive a message from the one or more neighboring modules in the same row or column as the programmable module, the message inquiring as to whether the programmable module can receive an item currently stored by the neighboring module; and update the current condition of the programmable module based on messages received from the neighboring modules.

In the programmable module, the control logic may send a message to a neighboring module in the same row as the programmable module, receive a response to the message from the neighboring module, and activate the transport mechanism of the programmable module in response to receiving the message from the neighboring module. In the programmable module, the control logic may receive a message from a neighboring module in the same column as the programmable module and activate the transport mechanism of the programmable module in response to receiving the message from the neighboring module. In the programmable module, the control logic may receive a message from a neighboring module in either the same row or the same column as the programmable module, in response to the message, determine if the programmable module is carrying an item, and if the programmable module is carrying an item, propagate the message to a neighboring module other than the neighboring module from which the message was received. In the programmable module, the control logic may receive a message from a neighboring module in either the same row or the same column as the programmable module, in response to the message, determine if the programmable module is carrying an item, and if the programmable module is not carrying an item, send a return message to the neighboring module from which the message was received. In the programmable module, the control logic may operate an item detector of the programmable module to determine the current condition of the programmable module, wherein the item detector comprises a sensing device, determine if the current condition satisfies the departure policy, and activate the transport mechanism of the programmable module if the current condition satisfies the departure policy.

GENERAL CONSIDERATIONS

In the foregoing description, numerous specific details, examples, and scenarios are set forth in order to provide a more thorough understanding of the present disclosure. It will be appreciated, however, that embodiments of the disclosure may be practiced without such specific details. Further, such examples and scenarios are provided for illustration, and are not intended to limit the disclosure in any way. Those of ordinary skill in the art, with the included descriptions, should be able to implement appropriate functionality without undue experimentation.

References in the specification to "an embodiment," etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is believed to be within the knowledge of one skilled in the art to effect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly indicated.

Embodiments in accordance with the disclosure may be implemented in hardware, firmware, software, or any combination thereof. Embodiments may also be implemented as instructions stored using one or more machine-readable media, which may be read and executed by one or more processors. A machine-readable medium may include any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computing device or a "virtual machine" running on one or more computing devices). For example, a machine-readable medium may include any suitable form of volatile or non-volatile memory.

Modules, data structures, blocks, and the like are referred to as such for ease of discussion, and are not intended to imply that any specific implementation details are required. For example, any of the described modules and/or data structures may be combined or divided into sub-modules, sub-processes or other units of computer code or data as may be required by a particular design or implementation. In the drawings, specific arrangements or orderings of schematic elements may be shown for ease of description. However, the specific ordering or arrangement of such elements is not meant to imply that a particular order or sequence of processing, or separation of processes, is required in all embodiments. In general, schematic elements used to represent instruction blocks or modules may be implemented using any suitable form of machine-readable instruction, and each such instruction may be implemented using any suitable programming language, library, application-programming interface (API), and/or other software development tools or frameworks. Similarly, schematic elements used to represent data or information may be implemented using any suitable electronic arrangement or data structure. Further, some connections, relationships or associations between elements may be simplified or not shown in the drawings so as not to obscure the disclosure.

This disclosure is to be considered as exemplary and not restrictive in character, and all changes and modifications that come within the spirit of the disclosure are desired to be protected.

The invention claimed is:

1. A method for arranging in an ordered sequence a number of physical items randomly presented to an automated material handling system having a plurality of programmable modules arranged in a grid, each of the programmable modules configured to at least temporarily store one of the items at a time and transfer the stored item to an neighboring module in an automated fashion, the grid comprising a plurality of rows in which items may travel bi-directionally and a plurality of columns in which items may travel bi-directionally, the method comprising, with the programmable modules:

admitting an item to the grid at a module of an entrance row of the grid;

determining a current address of the module at which the item is currently located in the entrance row, the current address defined by a row identifier and a column identifier;

determining a target address of a module at which the item is to be temporarily stored according to the ordered sequence, the target address defined by a row identifier and a column identifier;

determining if the column identifier of the current address corresponds to the column identifier of the target address;

if the column identifier of the current address does not correspond to the column identifier of the target address, activating a transport mechanism of one or more of the modules in the entrance row to move the item within the entrance row to the column of the target address;

if the column identifier of the current address corresponds to the column identifier of the target address, determining if the row identifier of the current address corresponds to the row identifier of the target address, and if the row identifier of the current address does not correspond to the row of the target address, determining a new address, the new address having a column identifier that corresponds to the column of the current address and the new address being closer in proximity to the target address than the current address; and

if another item is interfering with movement of the item to the new address, activating a transport mechanism of one or more of the modules in the row of the new address to temporarily move the interfering item to another module in the same row as the new address and activating a transport mechanism of one or more of the modules in the column of the new address to move the item to the new address.

2. The method of claim **1**, comprising, at each module of the entrance row, determining if the module is carrying an item and if the module is carrying an item, determining if the item is located at its target address.

3. The method of claim **1**, comprising, by the module receiving the item admitted to the entrance row of the grid, initiating a message to another module in the entrance row to request movement of the item to another column in the entrance row.

4. The method of claim **3**, comprising, by the module receiving the message, propagating the message to another module in the entrance row.

5. The method of claim **3**, comprising, by the module receiving the message, sending a return message to the module receiving the item admitted to the entrance row of the grid, wherein the return message indicates that the module receiving the message can accommodate the movement of the item to another column in the entrance row.

6. The method of claim **5**, comprising, in response to the return message, activating the transport mechanism of at least the module sending the return message and the module receiving the item admitted to the entrance row to move the item to another column of the entrance row that is closer to the column of the target address than the column of the current address.

7. The method of claim **5**, comprising activating the transport mechanism of each of the modules between the module sending the return message and the module receiving the item admitted to the entrance row to move each of the items located in the entrance row to another column of the entrance row.

8. A system for arranging a number of randomly presented physical items in an ordered sequence to be handled by a robot, the system comprising a plurality of programmable modules arranged in a grid, each of the programmable modules operable to at least temporarily store one of the physical items, transfer the stored item to a neighboring module, and communicate messages to other modules in the grid, the system to:

determine a target module at which the item is to be temporarily stored according to the ordered sequence, the target module having an address defined by a row and a column;

admit an item at a module of an entrance row of the grid,

move the item within the entrance row to the column of the target module;

move the item within the column of the target module to the row of the target module; and

move an item that interferes with the moving of the item toward the target module from its target position to a buffer column of the grid, the buffer column operable to temporarily store items that interfere with the movement of the item traveling toward the target module.

9. The system of claim **8**, to, by a module carrying the interfering item, initiate a message to other modules in the same row as the interfering item to request movement of the interfering item to the buffer column.

10. The system of claim **9**, to, by an empty module in the buffer column in the same row as the interfering item, send a return message to the module carrying the interfering item indicating that the empty module can assist with the movement of the interfering item.

11. The system of claim **10**, to activate the transport mechanisms of at least the module carrying the interfering item and the empty module to move the interfering item to the empty module.

12. The system of claim **11**, to, in response to determining that the interfering item is no longer interfering with the movement of the item traveling toward the target module, activate the transport mechanisms of at least the empty module and the module carrying the interfering item to return the interfering item to its target position.

13. The system of claim **9**, to receive return messages from a plurality of empty modules in the same row as the module carrying the interfering item and select a first to respond empty module of the plurality of empty modules to assist with the movement of the interfering item.

14. The system of claim **13**, to initiate movement of the interfering item in the direction of the selected empty module.

15. A programmable module comprising a transport mechanism and a computer component embodying control logic to control the operation of the transport mechanism, the transport mechanism operable to at least temporarily store a physical item and transfer the item to a neighboring module in a grid of programmable modules, the position of each of the programmable modules in the grid defined by a row and a column, the computer component operable to communicate messages to other modules in the grid, the grid of programmable modules operable to arrange a number of randomly presented items to exit the grid in an ordered sequence, the control logic of the programmable module to:

determine a current condition of the programmable module as one of empty, occupied, or seeking, wherein empty indicates that the programmable module is not currently storing an item, occupied indicates that the programmable module is storing an item that is in a target position defined for the item in accordance with the ordered sequence, and seeking indicates that the programmable module is currently storing an item that has not reached its target position;

determine if the current condition of the programmable module satisfies a departure policy, wherein the departure policy is satisfied if (a) all modules in the same column as the programmable module and all modules in all columns between the column of the programmable module and an exit column from which items exit the

grid, including the exit column, have a state of occupied or (b) all items to be sequenced are in the grid and at their target positions;

initiate a message to one or more neighboring modules in the same row or column as the programmable module to determine if the neighboring modules can receive an item currently stored by the programmable module;

receive a message from the one or more neighboring modules in the same row or column as the programmable module, the message inquiring as to whether the programmable module can receive an item currently stored by the neighboring module; and

update the current condition of the programmable module based on messages received from the neighboring modules.

16. The programmable module of claim **15**, wherein the control logic is to send a message to a neighboring module in the same row as the programmable module, receive a response to the message from the neighboring module, and activate the transport mechanism of the programmable module in response to receiving the message from the neighboring module.

17. The programmable module of claim **15**, wherein the control logic is to receive a message from a neighboring module in the same column as the programmable module and activate the transport mechanism of the programmable module in response to receiving the message from the neighboring module.

18. The programmable module of claim **15**, wherein the control logic is to receive a message from a neighboring module in either the same row or the same column as the programmable module, in response to the message, determine if the programmable module is carrying an item, and if the programmable module is carrying an item, propagate the message to a neighboring module other than the neighboring module from which the message was received.

19. The programmable module of claim **15**, wherein the control logic is to receive a message from a neighboring module in either the same row or the same column as the programmable module, in response to the message, determine if the programmable module is carrying an item, and if the programmable module is not carrying an item, send a return message to the neighboring module from which the message was received.

20. The programmable module of claim **15**, wherein the control logic is to operate an item detector of the programmable module to determine the current condition of the programmable module, wherein the item detector comprises a sensing device, determine if the current condition satisfies the departure policy, and activate the transport mechanism of the programmable module if the current condition satisfies the departure policy.

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